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14. ABSTRACT
Dense plasmas form a non-ideal, correlated state. We have recreated the plasma inside sono-luminescing bubbles with sparks and laser breakdown, which has dramatically simplified their study. These plasmas can be used for rapid, broadband optical switching and high-harmonic generation.

15. SUBJECT TERMS
dense plasma, laser breakdown, spark breakdown, non-ideal plasma, harmonic generation, debye sheath

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
UU	UU	UU	UU		Seth Putterman
					19b. TELEPHONE NUMBER
					310-825-2269

Report Title

Final Report: Noble Gas Plasmas with Metallic Conductivity: A New Light Source from a New State of Matter

ABSTRACT

Dense plasmas form a non-ideal, correlated state. We have recreated the plasma inside sono-luminescing bubbles with sparks and laser breakdown, which has dramatically simplified their study. These plasmas can be used for rapid, broadband optical switching and high-harmonic generation.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received		Paper
08/28/2015	4.00	Alex Bataller, John Koulakis, Seth Pree, Seth Putterman. Nanosecond high-power dense microplasma switch for visible light, Applied Physics Letters, (12 2014): 223501. doi:
09/04/2014	1.00	A. Bataller, B. Kappus, C. Camara, S. Putterman. Collision Time Measurements in a Sonoluminescing Microplasma with a Large Plasma Parameter, Physical Review Letters, (07 2014): 0. doi: 10.1103/PhysRevLett.113.024301
09/04/2014	2.00	Michael Schirber. Plasma Extremes Seen through Gas Bubble, Physics, (07 2014): 0. doi: 10.1103/Physics.7.72
09/04/2014	3.00	A. Bataller, G.?R. Plateau, B. Kappus, S. Putterman. Blackbody Emission from Laser Breakdown in High-Pressure Gases, Physical Review Letters, (08 2014): 0. doi: 10.1103/PhysRevLett.113.075001

TOTAL: 4

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Number of Presentations: 0.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received	Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received	Paper

TOTAL:

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received	Paper

TOTAL:

Number of Manuscripts:

Books

Received	Book

TOTAL:

Received Book Chapter

TOTAL:

Patents Submitted

Patents Awarded

Awards

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Seth Pree	0.50	
Alexandra Latshaw	0.50	
FTE Equivalent:	**1.00**	
Total Number:	**2**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
Adam Collins	0.25
John Koulakis	0.50
FTE Equivalent:	**0.75**
Total Number:	**2**

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Seth Putterman	0.13	
FTE Equivalent:	**0.13**	
Total Number:	**1**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:...... 0.00

Names of Personnel receiving masters degrees

NAME

Total Number:

Names of personnel receiving PHDs

NAME

Total Number:

Names of other research staff

NAME	PERCENT_SUPPORTED
Brian Naranjo	0.25
FTE Equivalent:	**0.25**
Total Number:	**1**

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

See Attachment

Technology Transfer

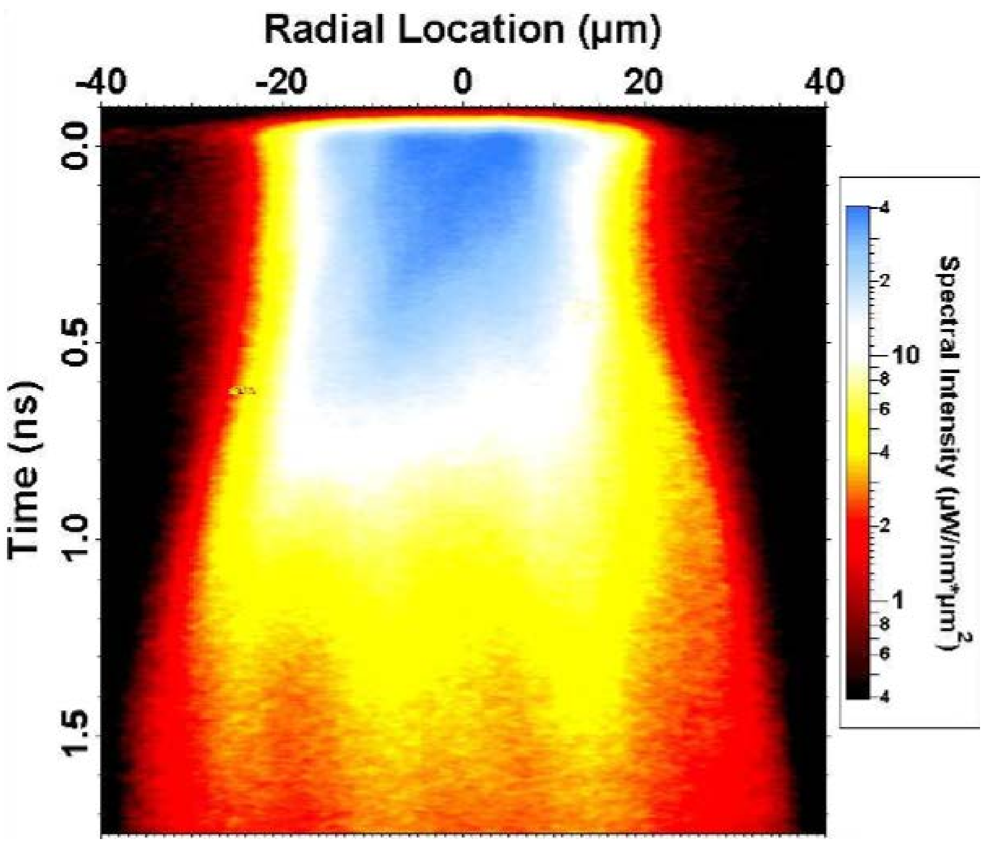
Noble Gas Plasmas with Metallic Conductivity: A New Light Source from a New State of Matter – W911NF1210001

Dan Purdy PM -- UCLA- Seth Putterman PI– November, 2015

FINAL REPORT

http://acoustics-research.physics.ucla.edu/

opportunities and mysteries



Alex Bataller, Alex Thornton,

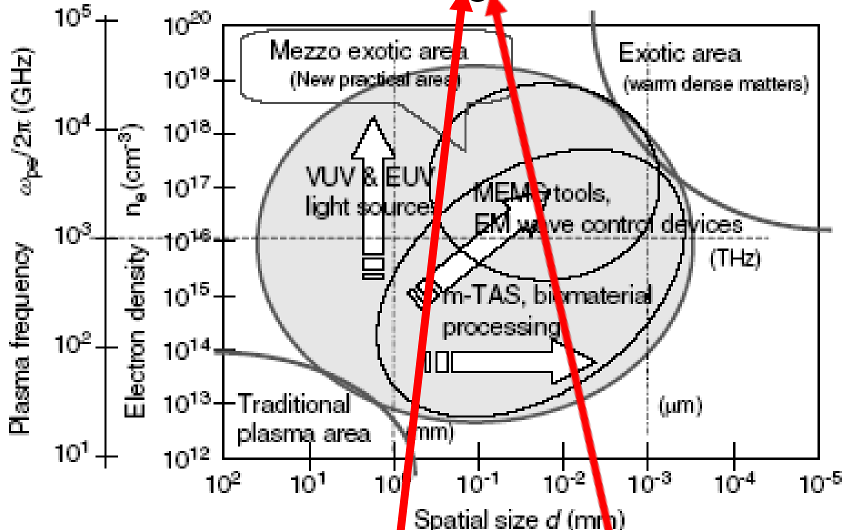
Alex Latshaw,

Seth Pree, John Koulakis

Dense microplasma condensate formed by laser breakdown

MicroPlasmas are Exotic Plasmas

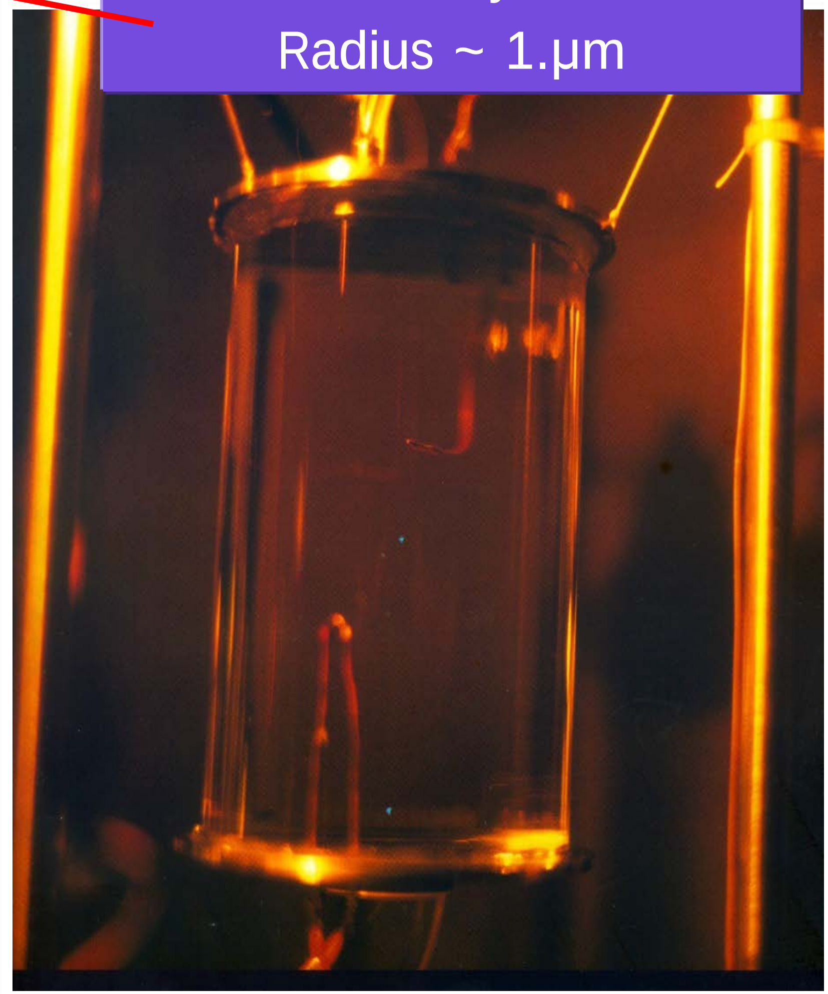
Tachibana

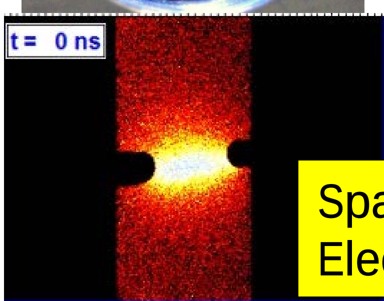


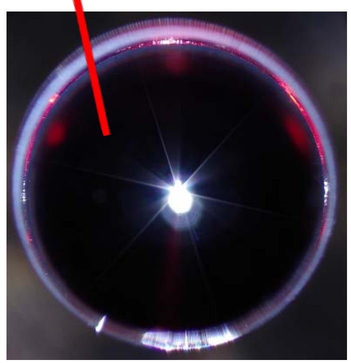
40.kHz ; flash width ~35.ps

Plasma density ~10^{22}/cc

Radius ~ 1.μm







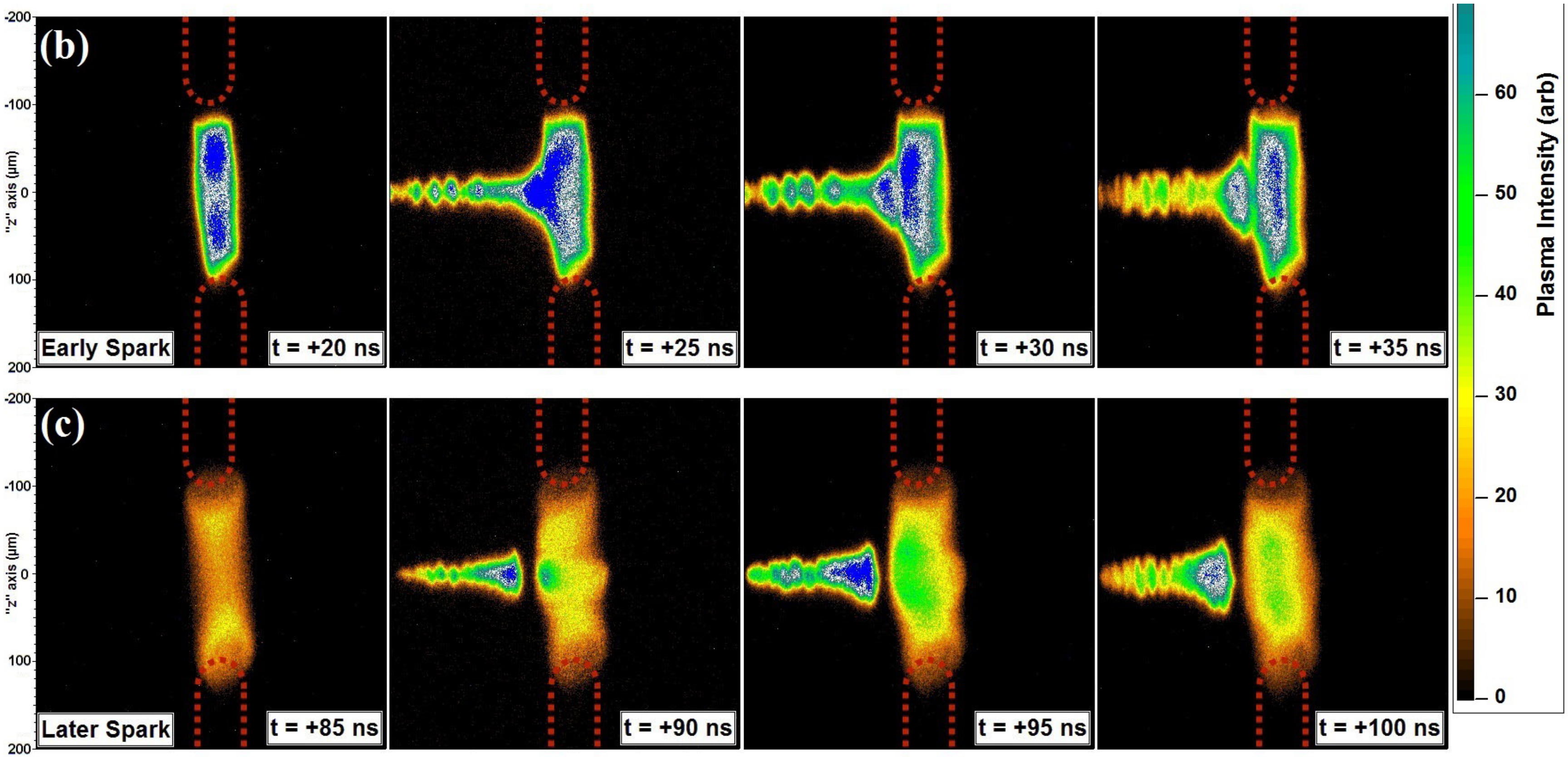
fs laser breakdown
In a dense gas

Spark discharge
Electrode spacing=100μm

Demonstration of Opaque Plasma Discharge Blocking Intense Laser Pulse-due to formation of dense plasma condensate

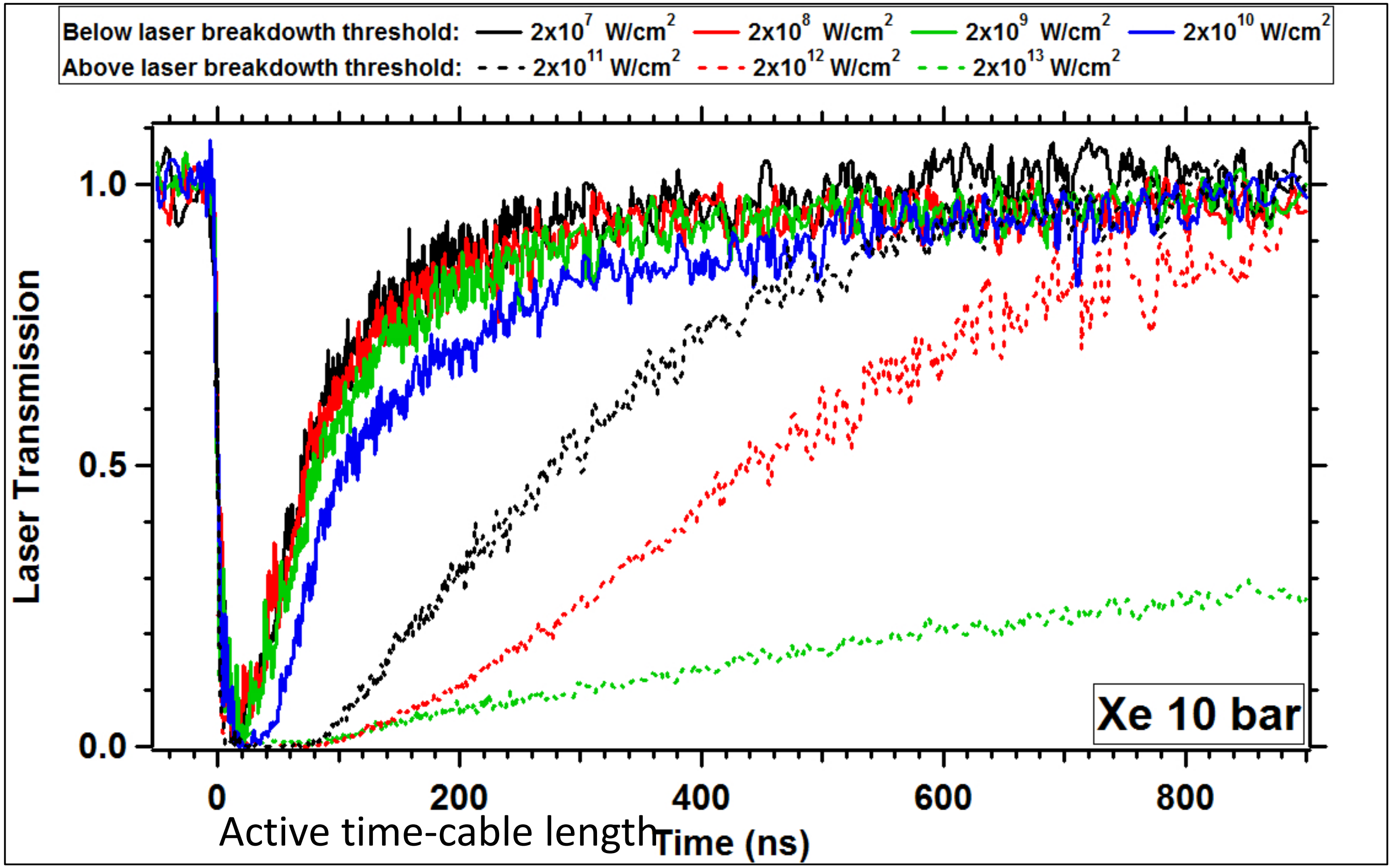
b) Intense laser pulse arrested at plasma surface

Practically limitless power handling capability. The switch cannot be broken as it is already the broken state of matter!



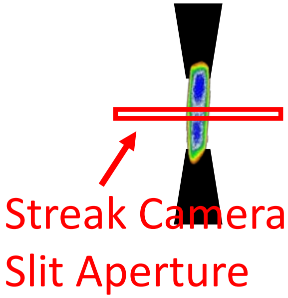
A. Bataller, J. Koulakis, S. Pree, S. Putterman, *Appl. Phys. Lett.* **105**, 223501 (2014)

Blocking light over six orders of magnitude of intensity; rise time not resolved-here

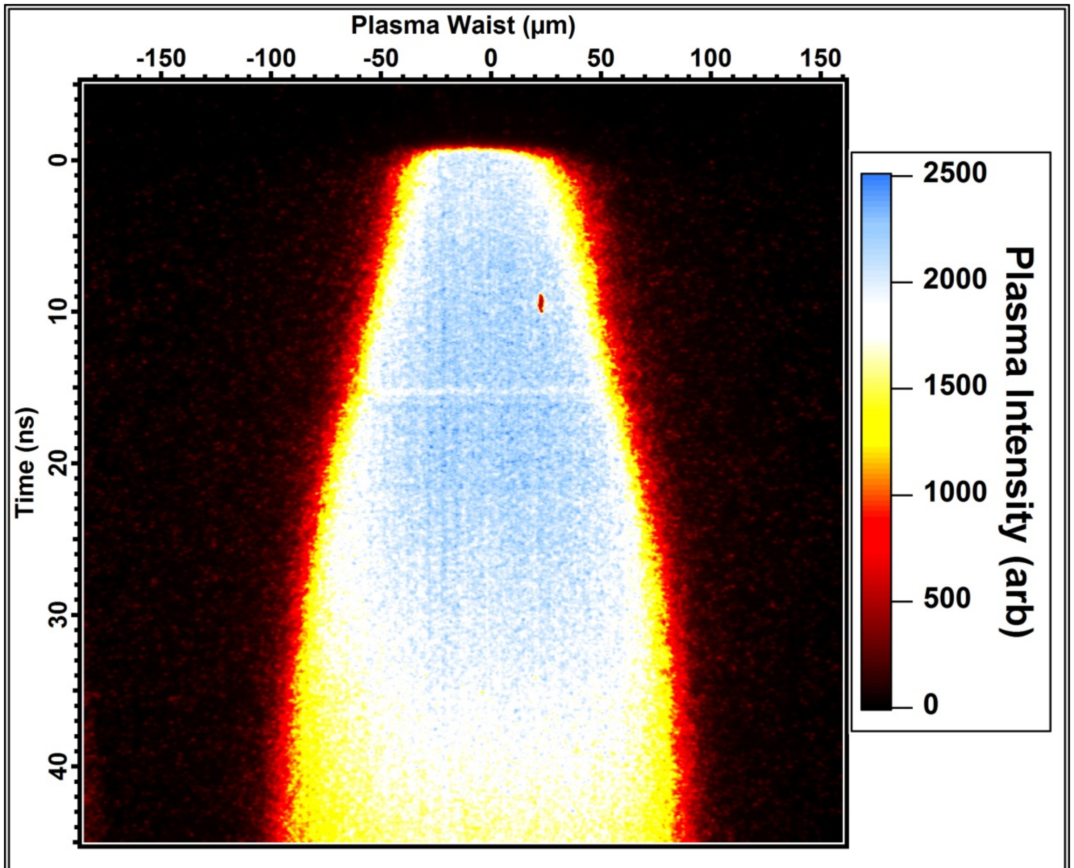


Normalized laser transmission of spark discharges formed in 10 bar xenon gas as a function of time and spanning 6 orders of magnitude in laser intensity. Laser transmission was recorded for 532 nm laser pulses focused through the center of the spark plasma. Intensities below the laser breakdown threshold (solid curves) produced nearly identical transmission curves indicating a linear laser-plasma response. Intensities above the laser breakdown threshold (dashed curves) deviated from the former curves with an increasingly nonlinear laser-plasma response, resulting in greater opacity for a longer period of time.

Switch Turns on Sub-ns
Blackbody is Established Within a Few Microns

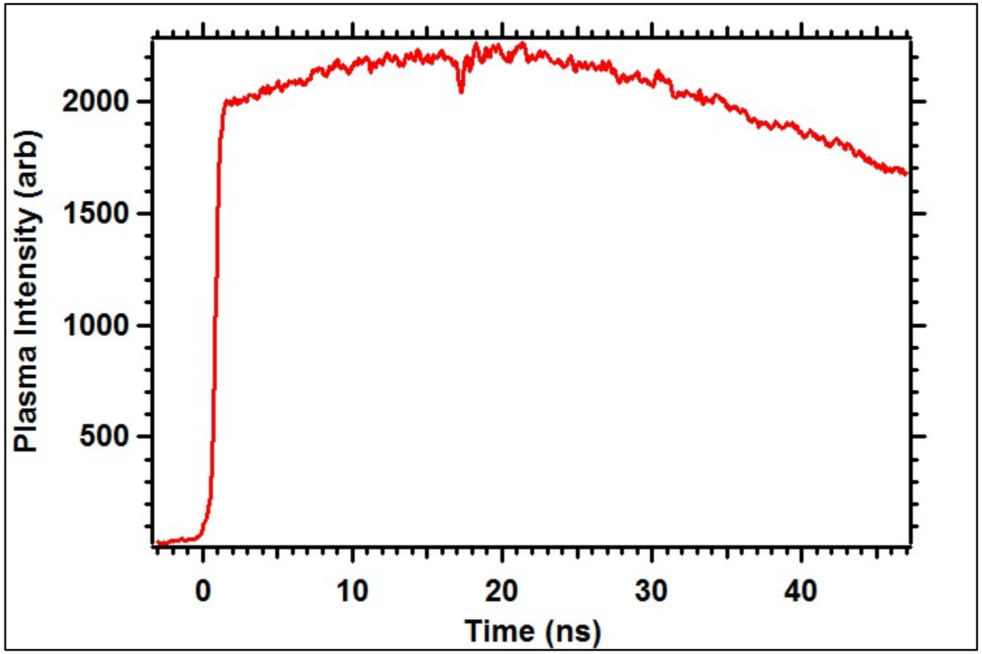


Sun is evenly bright and that is typical of a BB– contrast to a projection lamp

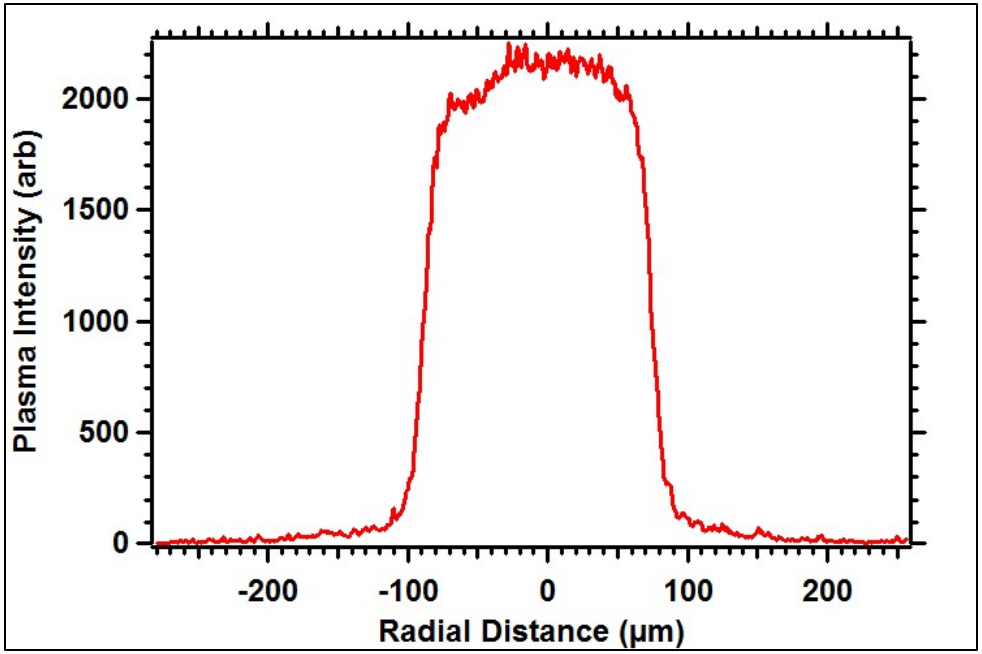


- Plasma is opaque within 500 ps making for an easier switch!
- Plasma opaque within 4 µm
- Plasma surface temperature (24,000K) is uniform in both time and space. The reason for this is unknown and points toward fundamental plasma processes.
- Plasma expansion is 2 km/s and points towards a hydrodynamic expansion…or perhaps an ionization wave?

Temporal and Spatial Line-Outs

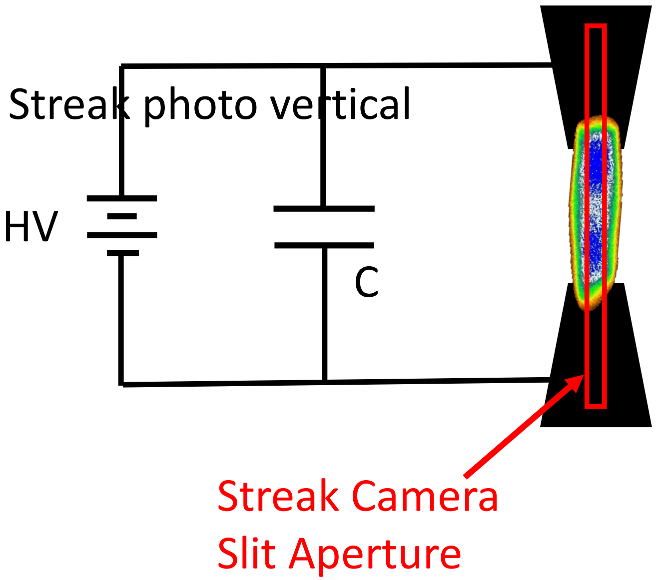


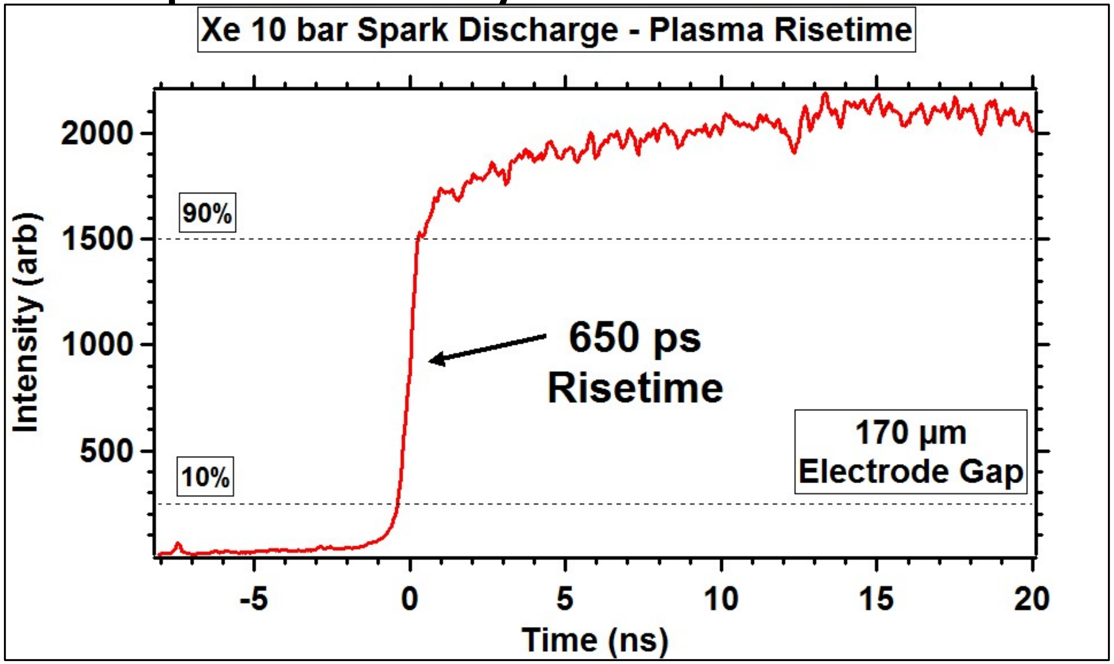
Temporal line-out: Intensity flattop in time shows a uniform temperature in time and a blackbody which blocks incident light for over 20 ns.



Spatial line-out: Intensity flattop in space infers a blackbody. Furthermore, the plasma has a uniform temperature across the plasma surface. This feature is robust and not fully understood.

Sub-Nanosecond Opacity Switch
Opacity Rise Time is as fast as spark rise time and 3x faster than simple mobility model





Randomly triggered by uv lamp

Spark transit time estimate:

based on electron mobility in xenon gas

$t=L^2/\mu V= 1.9$ ns, roughly consistent with observations – MPD is about 3 times FASTER than simple mobility model.

for L=170 μm, V=5000kV, μ=30 cm^2/Vs

μ from Huang and Freeman 1977

Temporal line-out

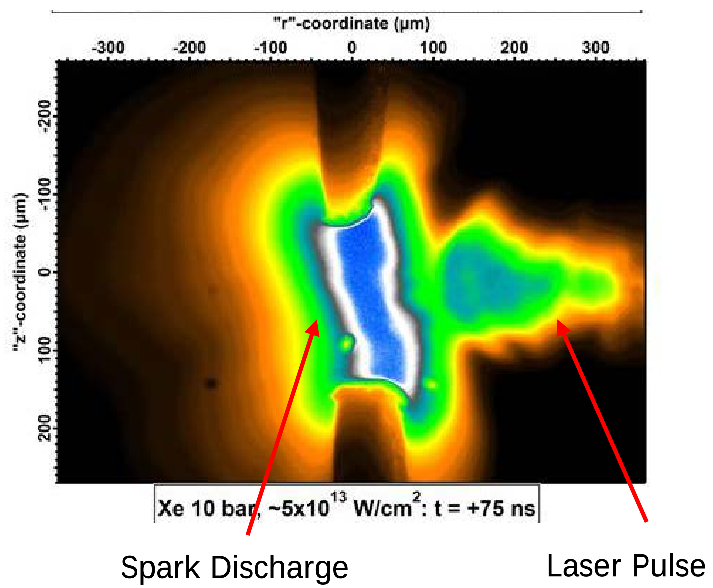
Discharge reaches opacity in ~0.1% the speed of light!

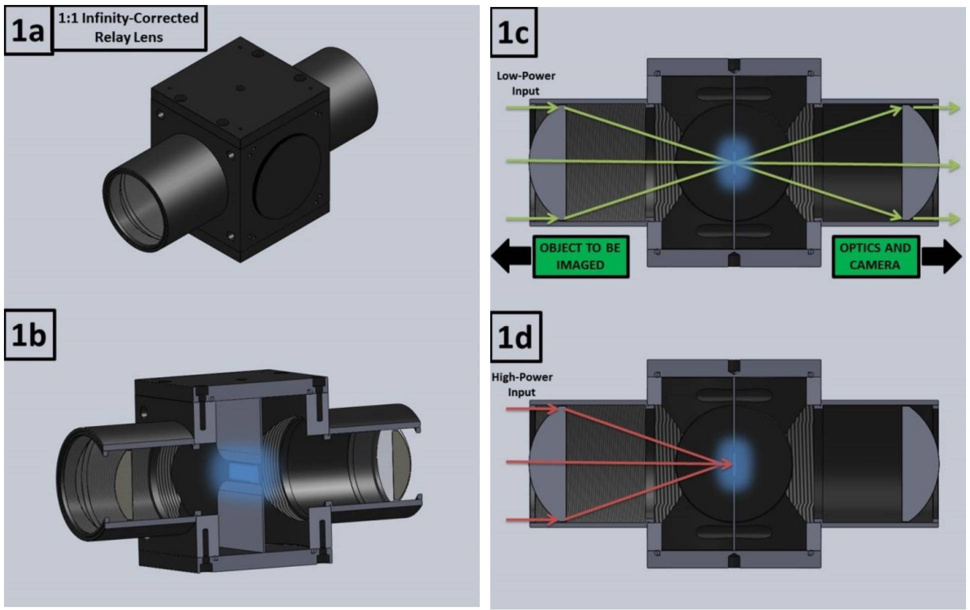
Can block leading edge

High-Power Dense Microplasma Optical Switch:

Dense Plasmas are Ideal for High Power Switching Because A Plasma is the Broken State of Matter

Spark Blocking Laser Pulse that is Incident from the Right





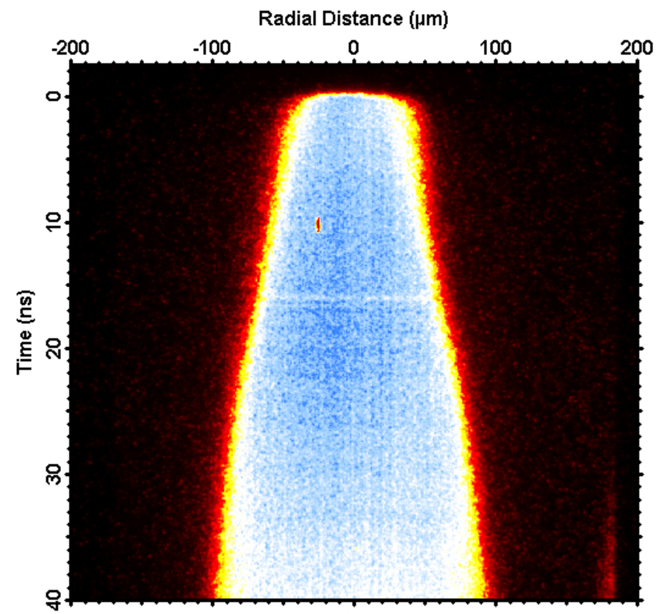
Spark is capable of blocking high-power laser pulse, with nearly infinite power-handling capability. Protect sensitive equipment or select individual laser pulses.

Plasma Shield

"Leading Edge" can be blocked
(with adapted device – not pictured)

Dense Microplasma Intensity Saturation

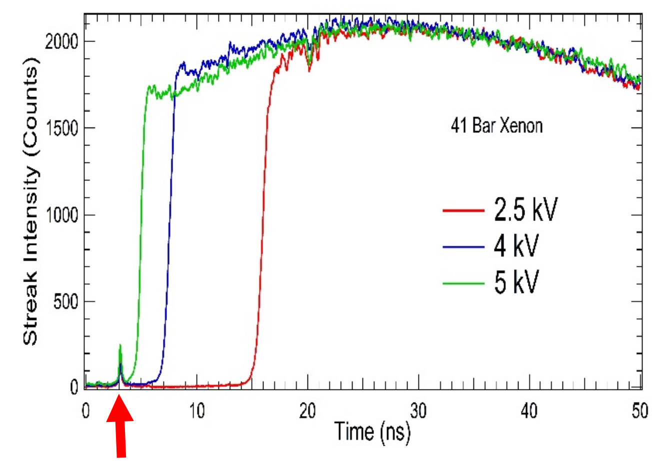
- Universal energy-density-limiting phenomenon seen in sonoluminescence, sparks, laser breakdown, and nuclear explosions.
- Review 1958 Vanyukov and Mak: *“High-Intensity Pulsed Light Sources.”*
- Explanation has been debated for >50 years.
- Yusupaliev: energy out increases too rapidly to be overcome with any system → determines limiting temperature.
- T_{lim} is only gas dependent, system irrelevant.
- Uniform in space, time, voltage, pressure, gap distance
- Could make excellent calibration source.



Xenon 10 bar - 5 kV Discharge

Gas	$T_{\rm LIM}$, K	$\Xi_{\rm LIM}$	$I_f(I_{\rm eff})$, eV	I_2, eV	$\frac{kT_{\rm LIM}}{I_1+I_2}$	
Xe	27000–29000 (2.33–2.5)	2.0	12.13	21.20	0.072	0.074
	30000				0.076	
Kr	32000 (2.76)	2.6	13.90	24.60	0.071	
	34000 (2.93)				0.076	0.073
Ar	35000 (3.0)	4.0	15.76	27.60	0.070	
	37000 (3.187)				0.074	0.072
Air	43000 (3.7)	5.6	16.0	32.36 oxygen atom		0.076
N_2	41000 (3.53)		16.5	29.60		0.077
Ne	52000 (4.48)	6.5	21.56	40.96		0.072
He	67000–71000 (5.77–6.12)	8.0	24.59	54.42	0.073	
					0.077	0.075

U. Yusupaliev 2010, also see 2012



Fs laser-breakdown seed

Luminosity Saturation in other systems: Sonoluminescence

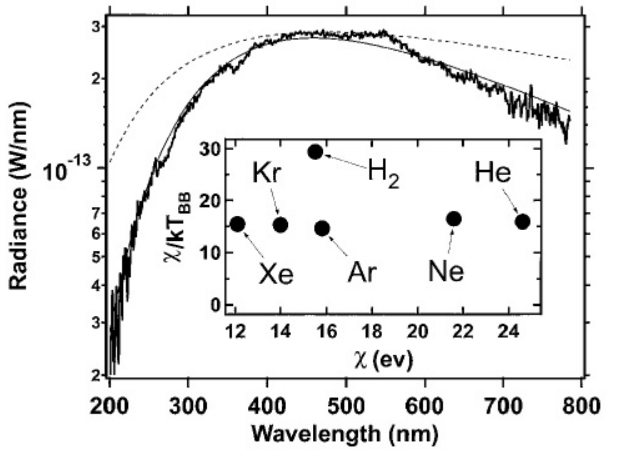
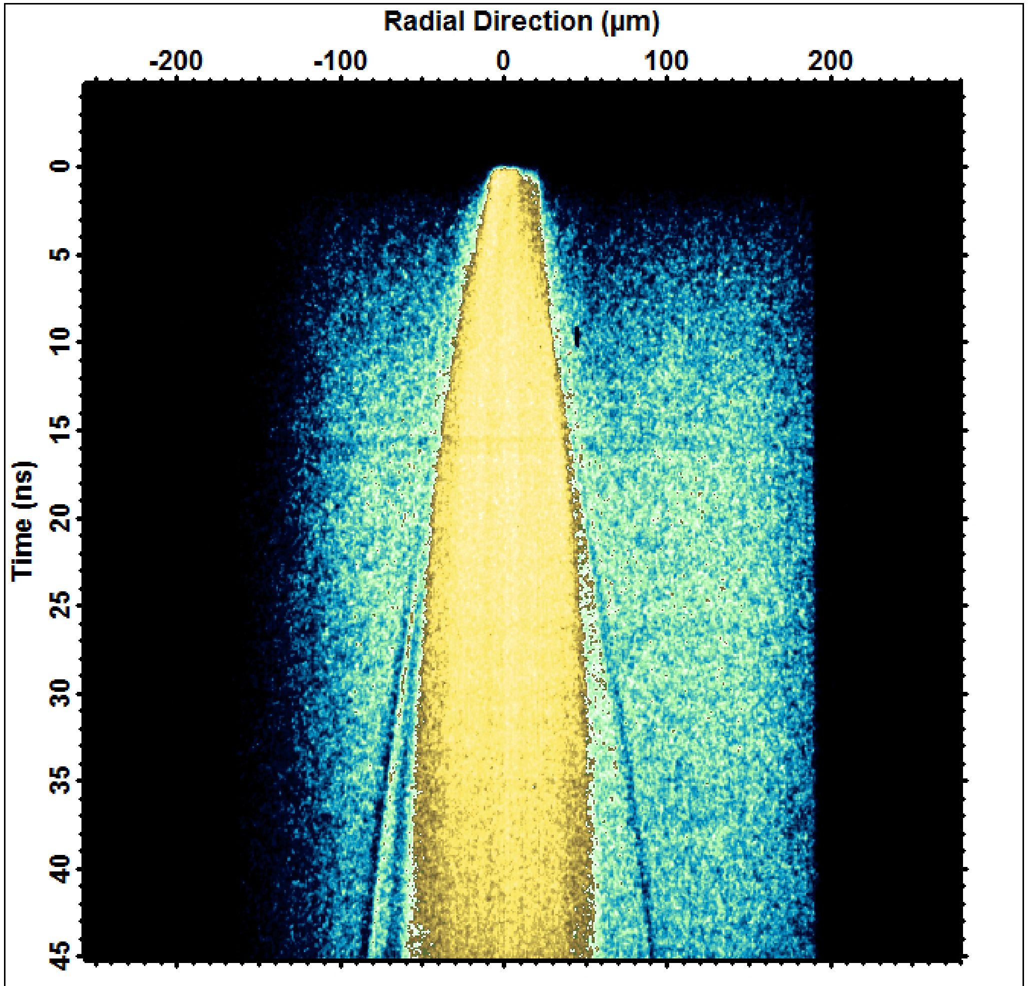


Fig. 1. Spectrum (resolution, 24 nm FWHM) of 33-kHz SL from a bubble formed in water (23 °C) into which H_2 was dissolved at a partial pressure of 5 Torr. Solid curve, fit to a blackbody at 6230 K. According to Eq. (1), the flash width of 110 ps requires emission from a surface with radius 0.22 μm. Dashed curve, bremsstrahlung fit with a temperature of 15,000 K. Inset, plot of χ/T_{BB} as a function of χ, the ionization potential of the gas used to make SL.

G. Vazquez, C. Camara, S. Putterman, and K. Weninger

- For a well-controlled system of water Sonoluminescence, where system parameters are kept fixed and gases are varied, $\chi / k_B T$ = constant
- Almost all Sonoluminescence (1 MHz is the only exception) indicates a maximum achievable temperature of ~20,000 K, no matter how hard it is driven. Energy appears to be converted to a larger size (Ramsey, Cone Bubble, Shake Tube, Drop Tower).

Shock Wave Emission from a Dense MP



Xe 10 Bar Spark Discharge

- Shock waves tell us hydrodynamic motion and that the plasma is expanding. This guides our efforts in both studying the dense plasma and designing an optimum switch.
- Shock waves also tell us the initial plasma energy and gives information towards an equation of state.

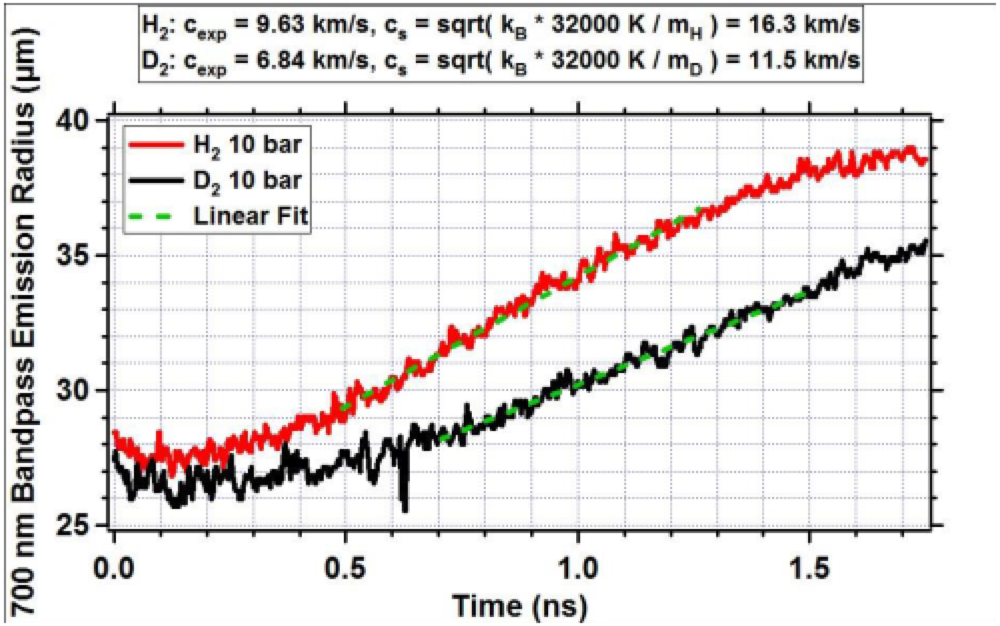
Although the field is as old as electricity, many spark discharge features remain unknown:

"We have pointed out that the problem of streamer head radius still remains to be solved. Today, there is no adequate theory, nor is there convincing experimental evidence to determine the head size reliably."

-Raizer, "*Spark Discharge*" 1998

Dwell Time of Plasma Condensate

Ambient pressure before breakdown = 10.atm
Electron temperature after breakdown = 25,000K
Pressure. 3,000.atm
Plasma charge density ~ 10^{21}/cc
Yet H plasma dwells for 200ps; D plasma for 400.ps



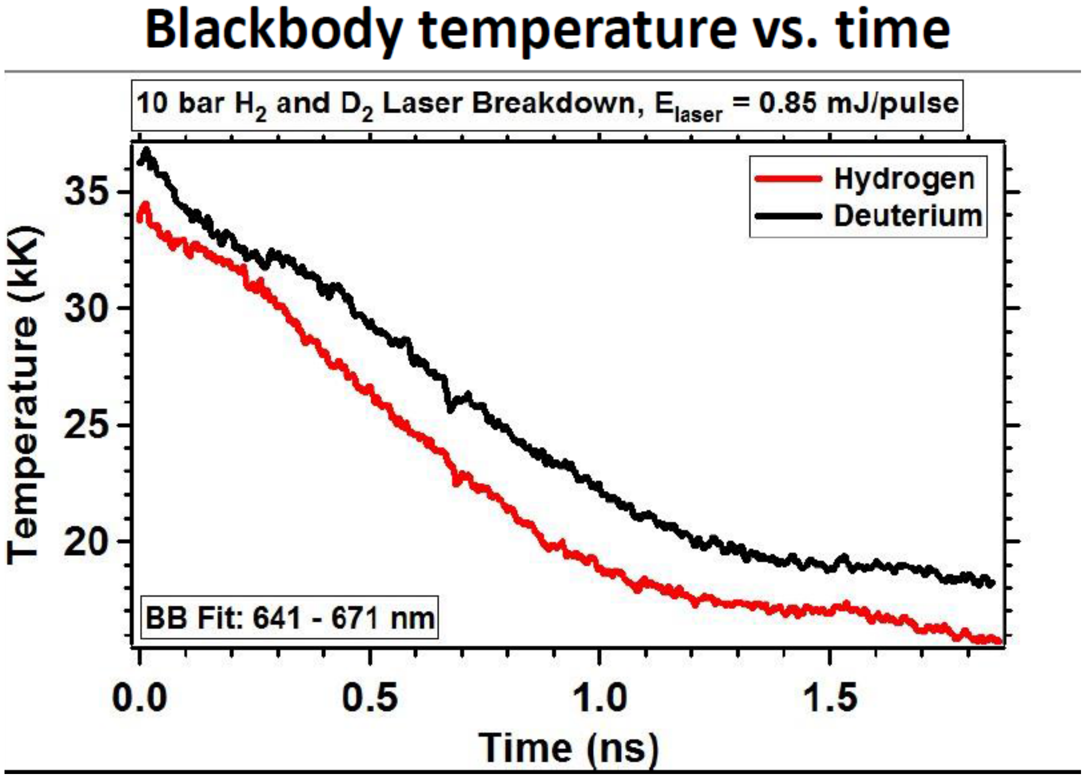
Plasma Parameter= Γ ; a~ 8A

$$\Gamma = e^2 / akT \; ; \; a = (3 / 4\pi n_e)^{1/3}$$

If the ions are at ambient Temperature
then Γ(ions) = 70
Which is very strong coupling

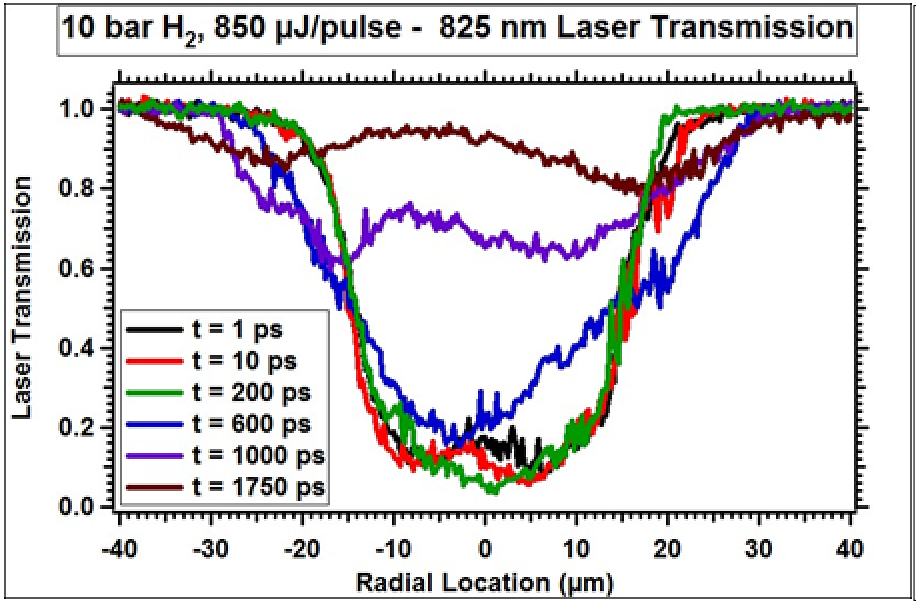
Electron- IonAcoustic phonon Interaction Dominates Thermalization

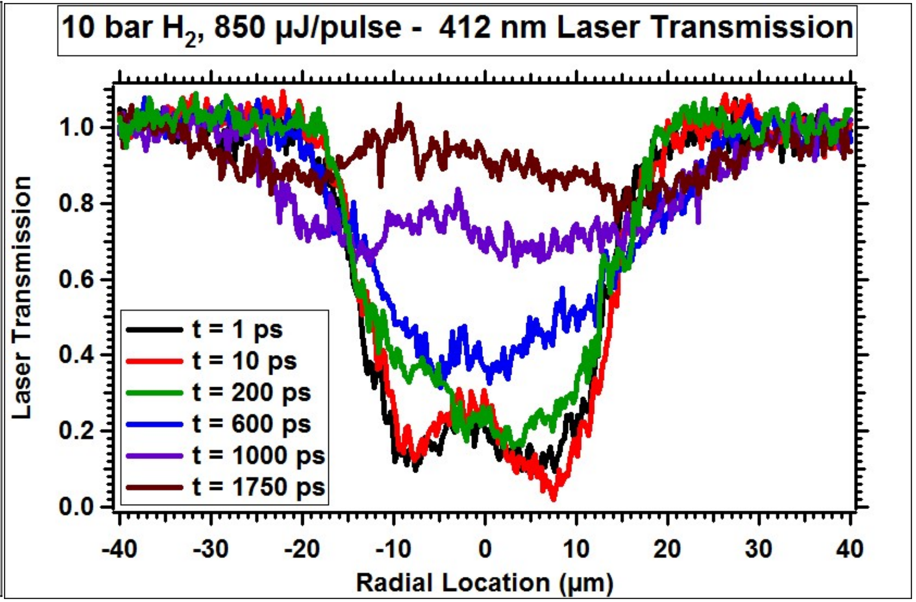
Ions and electrons should equilibrate in 10ps, but interaction is much slower, because energy transport in a plasma condensate is not due to binary collisions but is more like much weaker electron- phonon interacions.

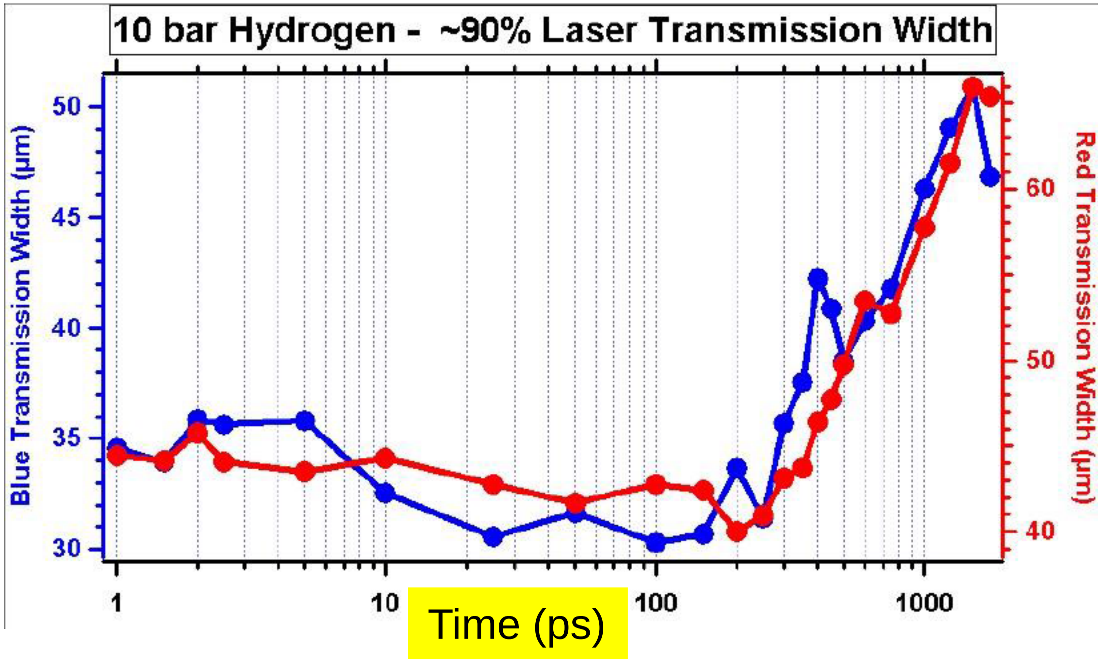


Is reduced scattering during dwell the key to achieving energy densities beyond the Yusupaliev limit?

Transmission measurements also match emission waist dwell times

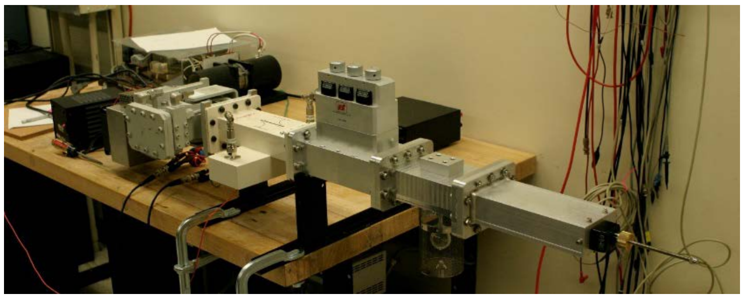




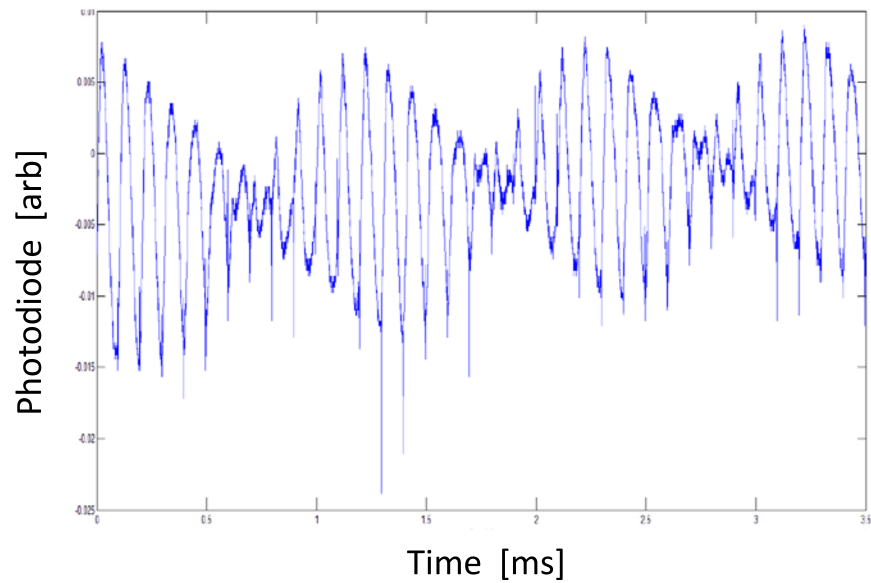


Resonant Ion Acoustic Waves in Plasma Bulb

- We can excite resonant acoustic modes in plasma bulb.
- Can they be used to: 1) gain insight into ion behavior.
  2) confine/stabilize dense plasma.



Beating between ~10kHz drive frequency and nearby natural mode.



Can one achieve a confined steady state dense plasma

Plasma Harmonic Generation

Plasmas are intrinsically nonlinear especially at boundaries- where a sheath forms

Characteristic length for plasma sheath is:

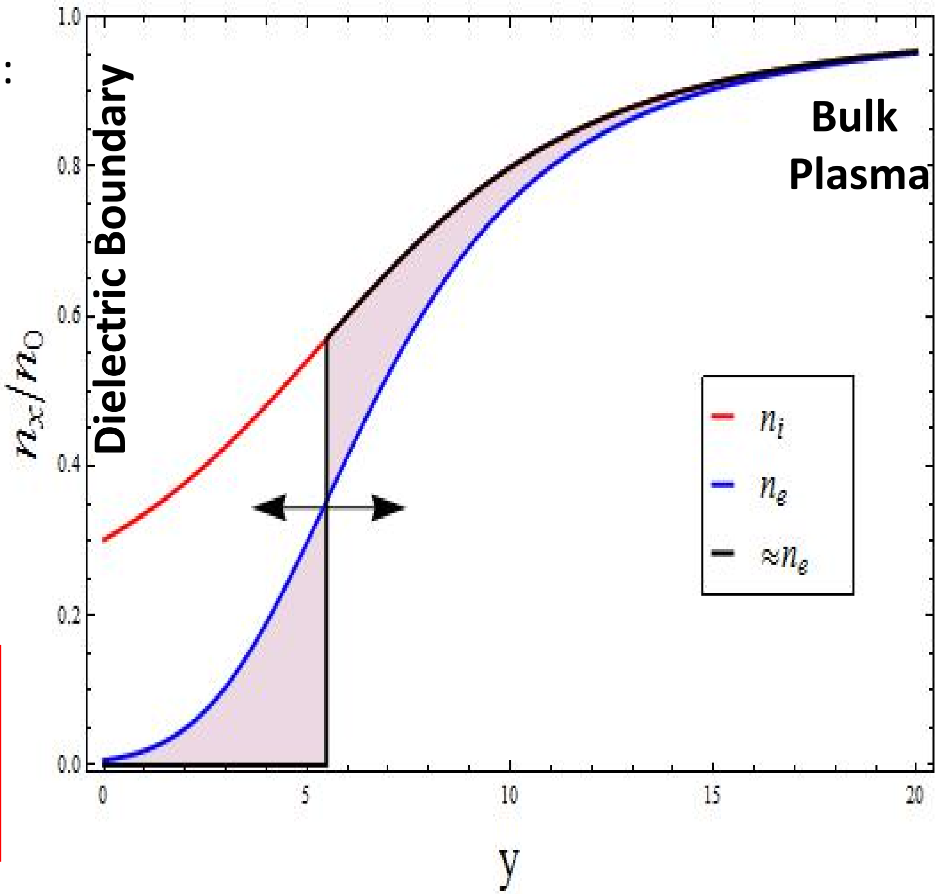
$$\delta = \sqrt{\varepsilon_0 k T_e / e^2 n_0}$$

Dielectric boundary becomes charged so:

$$e\varphi / kT_e \sim 5$$

Electron fluid oscillates in the static potential field of the ions

If amplitude of oscillation ~ δ
we can expect non-linear
behavior in the sheath region



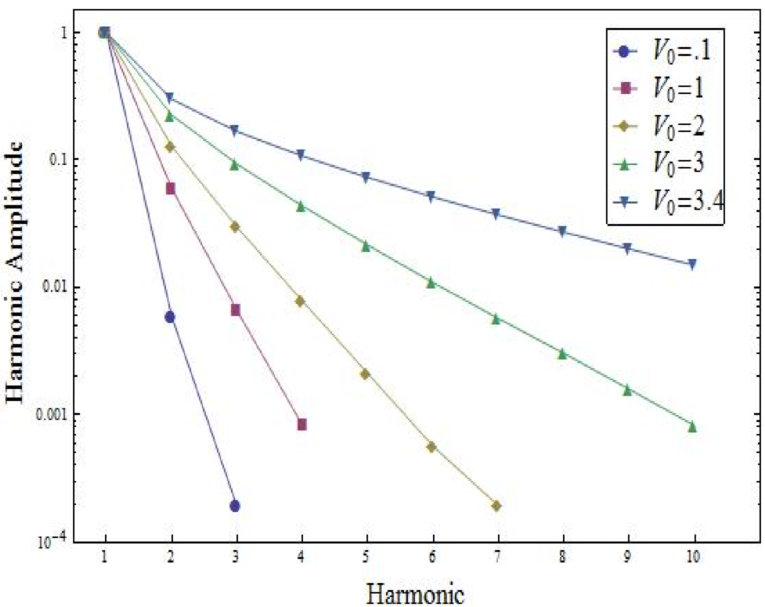
Non-linear Sheath Interaction

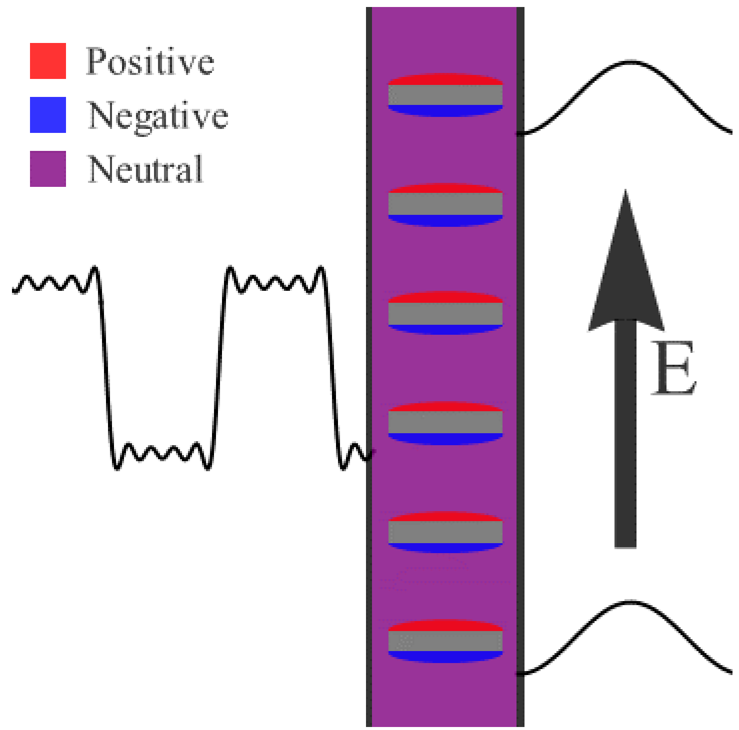
- Use external field to drive plasma to slosh between dielectric plates, forming dipoles with non-linear response.

$$\delta = \sqrt{\varepsilon_0 k T_e / e^2 n_0} = 700 \text{ nm} \quad \text{for } T=10{,}000 \text{ K}, \; n_e = 10^{14} \text{ /cm}^3$$

$$x_0 = \frac{qE_0}{m\omega^2} = 3 \text{ um} \quad \text{for } E_0 = 100 \text{ kV/m at 2.5 GHz}$$

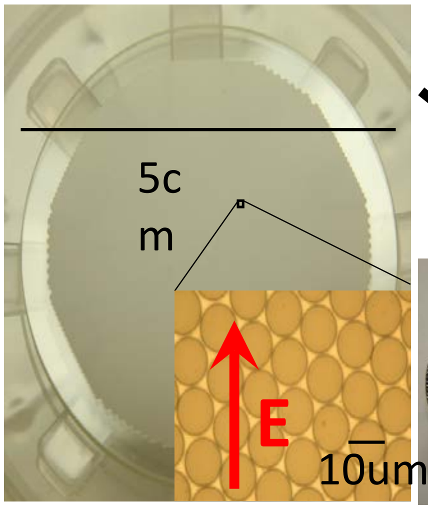
- Dipoles can be arranged for optimal harmonic radiation



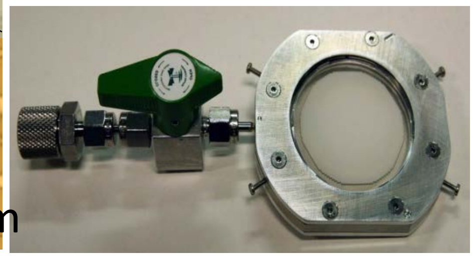


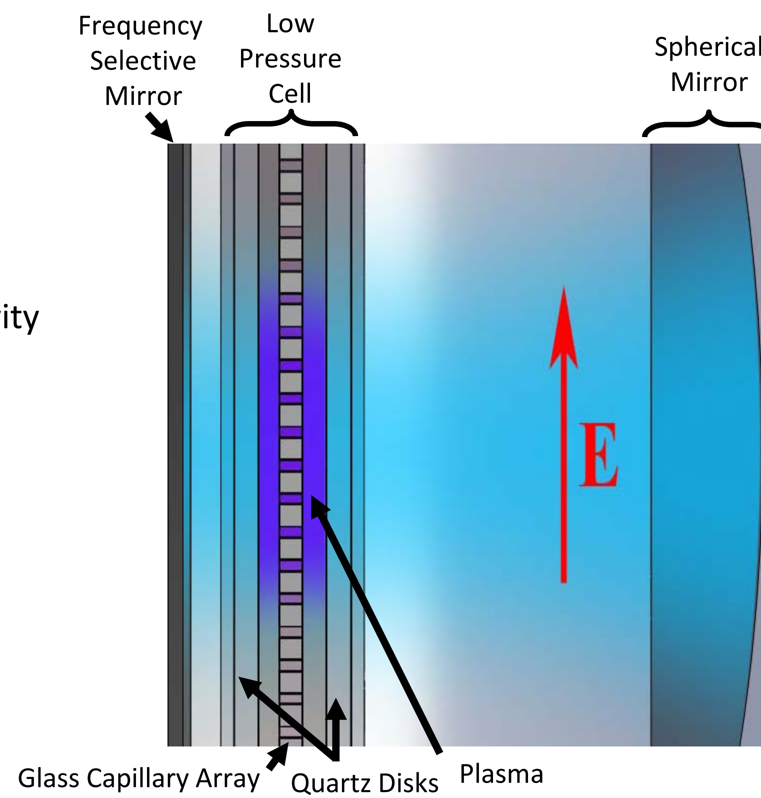
Non-linear Sheath Interaction - Practice

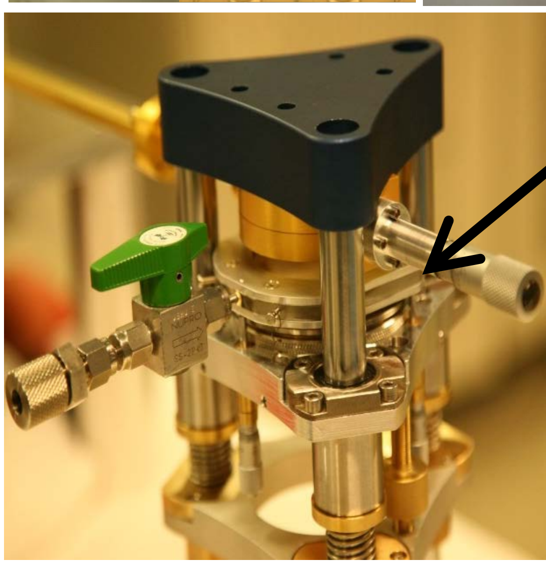
Glass Capillary Array



- Plasma is generated inside the low pressure cell, and diffuses into the capillary array.
- The field forces the plasma to slosh back and forth non-linearly.
- Each capillary can be viewed as one element of an antenna array radiating into the cavity







and into microwave cavity

Inserted into low pressure cell

Recent Accomplishments under MPD Program at UCLA- Submitted by Seth Putterman ; Aug 7, 2015

- **Evidence that a metallic proton fluid microplasma forms under rapid ionization of hydrogen gas**
  Based upon our plasma dwell time measurements 2015

- **Hydrogen microplasma has a long lived hot electron gas**
  Based upon spectral measurements and explained by reduced scattering crossection
  with protons due to their liquid properties. 2015

- **Isotope effect observed in rapidly ionized microplasma** 2015

- **Nanosecond switch with infinite power handling capabilities from UV to IR**-2014
  APPLIED PHYSICS LETTERS 105, 223501

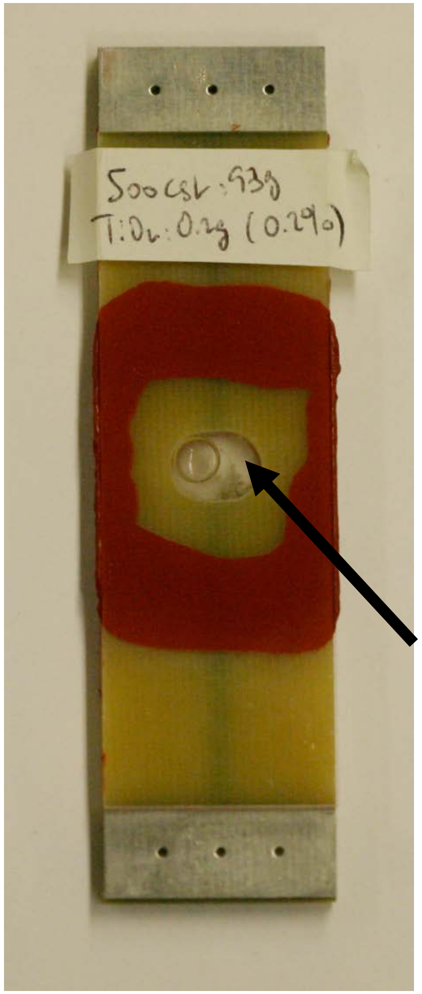
- **Screening increases the time between collisions in a dense plasma-** 2014
  Phys. Rev. Lett. 113, 024301
  http://physics.aps.org/articles/v7/72 News Story Physics Focus- “Plasma Extremes”

Nature likes to form dense microplasmas when gases are energized. We have seen that this can be achieved with
Acoustics = sonoluminescence, Electrically = sparks; and Optically = laser breakdown
Condensate , opacity , dwell, resonant plasma acoustics.
These plasmas offer new equations of state; opportunities for new devices, including hhg

Laser Breakdown Lowering

- Liquids categorically have a breakdown threshold ~10x lower than gases.
- Adding impurities to liquid can lower threshold another 3-10x.

Circuit boards made as a simple fast method of measuring Optical prop and resistivity.



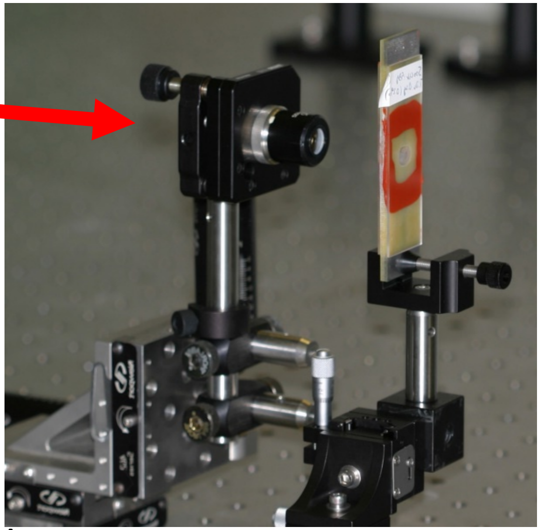
Silicon Oil with 0.2% TiO_2

Potential active-medium: Silicon oil with or without additives

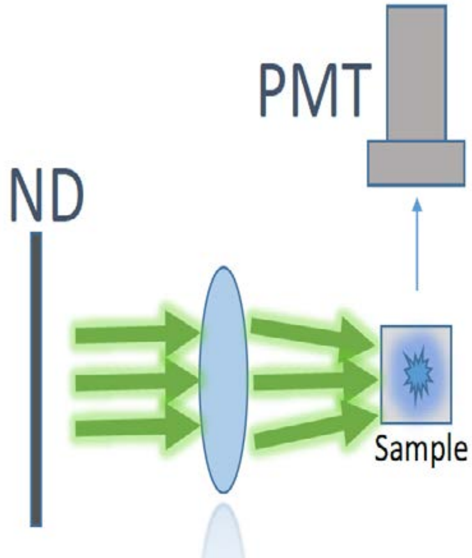
Benefits:
- Transparent
- Heals after breakdown
- Stable. Can withstand high, used in HV caps
- High resistivity
- Added impurity: dispersed TiO_2 nanoparticles

Optical Arrangement for quickly testing optical breakdown of liquid mixtures:

Incoming Laser



Thickness fiberglass board 2mm conductivity and optical accessibility--



Substance	Intensity for breakdown, W/cm^2 2.1 ns 532 nm pulse.
Air	$5 * 10^{11}$
10 Bar Xe	$2 * 10^{11}$
Water	$1.3 * 10^{11}$ +- $.4 * 10^{11}$
Si Oil	$5 * 10^{10}$ +- $1 * 10^{10}$
Si Oil with .001% TiO_2	$3 * 10^{10}$ +- $1 * 10^{10}$

The observed reduction in the laser breakdown threshold of silicone oil as compared to high pressure xenon demonstrates that the dense plasmas studied throughout this program may be achievable with less energy when seeded in a denser precursor. This discovery widens our present ability to study how such plasmas handle excess energy beyond what is necessary for plasma formation. Knowing whether the excess is consumed for further local ionization, deposited into a larger profile, dissipated as heat, or radiated acoustically would inform on the limits of creating this state of matter. Additionally, these results indicate a need to examine the time scales over which plasma formation occurs in a more highly correlated starting medium. Such research may give insight into the sub-nanosecond turn-on times observed following the femtosecond laser-seeded high voltage breakdown.